

Measurements of Photocathode Operational Lifetime at Beam Currents up to 10 mA using an Improved DC High Voltage GaAs Photogun

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Abstract. This work extends past research at Jefferson Lab aimed at better appreciating the mechanisms that limit photocathode operational lifetime at high current (> 1 mA). Specifically, the performance of an improved 100 kV DC high voltage load locked photogun will be described. Although difficult to measure directly, we believe the new gun has better vacuum conditions compared to the original gun, as indicated by enhanced photocathode lifetimes exceeding 2000 C using a 1.55 mm diameter drive laser spot at the photocathode. In addition, the dependence of the lifetime on the laser spot size at the photocathode was measured and a charge density lifetime exceeding 10^6 C/cm² was measured with a 0.32 mm laser spot diameter.

Keywords: Electron sources; Polarized beams; Particle sources and targets; Vacuum systems

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INTRODUCTION

DC high voltage GaAs-based photoguns are key components at accelerator facilities worldwide. Today's state-of-the-art photoguns operate reliably at ~ 200 μ A average current with high polarization [1] and at ~ 5 mA with no polarization [2]. Future accelerators [3-6] however expect to operate at considerably higher current and will require numerous technological advances, particularly in the fields of ultra-high vacuum (UHV), high voltage (HV) operation, drive laser technology, photocathodes and beam handling with high bunch charge. This work extends previous measurements performed at Jefferson Lab designed to better appreciate the mechanisms that limit GaAs photogun operation at high average current [7-9]. In particular, a new load locked photogun with improved vacuum characteristics was commissioned. Although difficult to measure directly vacuum pressure in the new gun is lower than the previous gun as evidenced by improved charge lifetime at beam currents from 1 to 10 mA. In addition, the new gun has features that simplify operation, enhance reliability and prolong the operating lifetime, as described below.

The new load locked gun was used to study the relationship between drive laser spot size at the photocathode and charge lifetime. A significant mechanism limiting photocathode operational lifetime of modern DC high voltage GaAs photoguns is ion back-bombardment, where residual gas in the cathode/anode gap is ionized by the

exiting electron beam and then accelerated back toward the photocathode. These ions damage the GaAs crystal structure or sputter away the chemicals that are used to create the negative electron affinity (NEA) condition of the photocathode. For a larger laser spot size, the ion damage will be distributed over a broader area and consequently, damage to specific photocathode locations will occur more slowly. This work confirms results first reported in reference [9], namely, markedly improved charge lifetime can be obtained using a larger laser spot size at the photocathode, however, we find charge lifetime does not scale with laser beam area as predicted by a simple model. Together with the improved vacuum associated with the new gun design, we report a charge lifetime > 2000 C using a 1.55 mm laser spot size and a charge density lifetime $> 10^6$ C/cm² using a 0.32 mm diameter laser spot size. To our knowledge, these are the highest GaAs photocathode charge and charge density lifetime values ever reported at beam currents > 1 mA.

NEW LOAD LOCKED ELECTRON GUN

The new load locked gun (Fig. 1) consists of four chambers separated by UHV all-metal vacuum gate valves; 1) a portable “suitcase” chamber, 2) a loading chamber, 3) a photocathode preparation chamber and, 4) a high voltage (HV) chamber. As with all load locked guns the best vacuum is obtained in the high voltage chamber (more below). Magnetically-coupled manipulators are used to transfer photocathode samples between chambers. Bulk GaAs samples (600 μ m thick zinc doped GaAs crystal) were used for these measurements. Each sample was indium soldered to a molybdenum “puck” and captured beneath a tantalum retaining ring. The new gun can accommodate four pucks, a significant improvement over the original load locked gun design that could manage only one photocathode sample. Multiple pucks reduce downtime associated with photocathode replacement, thereby enhancing the operating lifetime of the gun.

Four pucks were introduced to the suitcase chamber using a nitrogen filled glove bag and then transported and mated to the loading chamber. For this experiment, the suitcase and loading chambers were baked at 150°C [10] for 12 hours. In the future, we will bake the suitcase in our photocathode lab and only the isolated intermediary loading chamber will require a bake-out. The loading chamber contains only a 20 L/s ion pump that provides pressure $\sim 10^{-9}$ Torr.

Following bake-out, the two valves separating the suitcase, loading and preparation chambers were opened and the pucks were transferred to storage docks within the preparation chamber using manipulators. Once the transfers were completed the valves were closed and only the suitcase chamber was removed, under vacuum, to a convenient location. The preparation chamber contains commercial non-evaporable getter (NEG) pumps with combined pump speed of 800 L/s and a 40 L/s diode ion (DI) pump to maintain a base pressure of $\sim 10^{-10}$ Torr, with hydrogen the dominant gas species as measured by a residual gas analyzer. An individual puck was positioned atop a heater and heated to 575°C for 12 hours. It was then cooled to room temperature and moved toward a mask used to limit the active area of the photocathode (5 mm diameter). The photocathode was activated with cesium and nitrogen trifluoride using the “yo-yo” technique. A 780 nm diode laser and 100 V bias were used for activation.

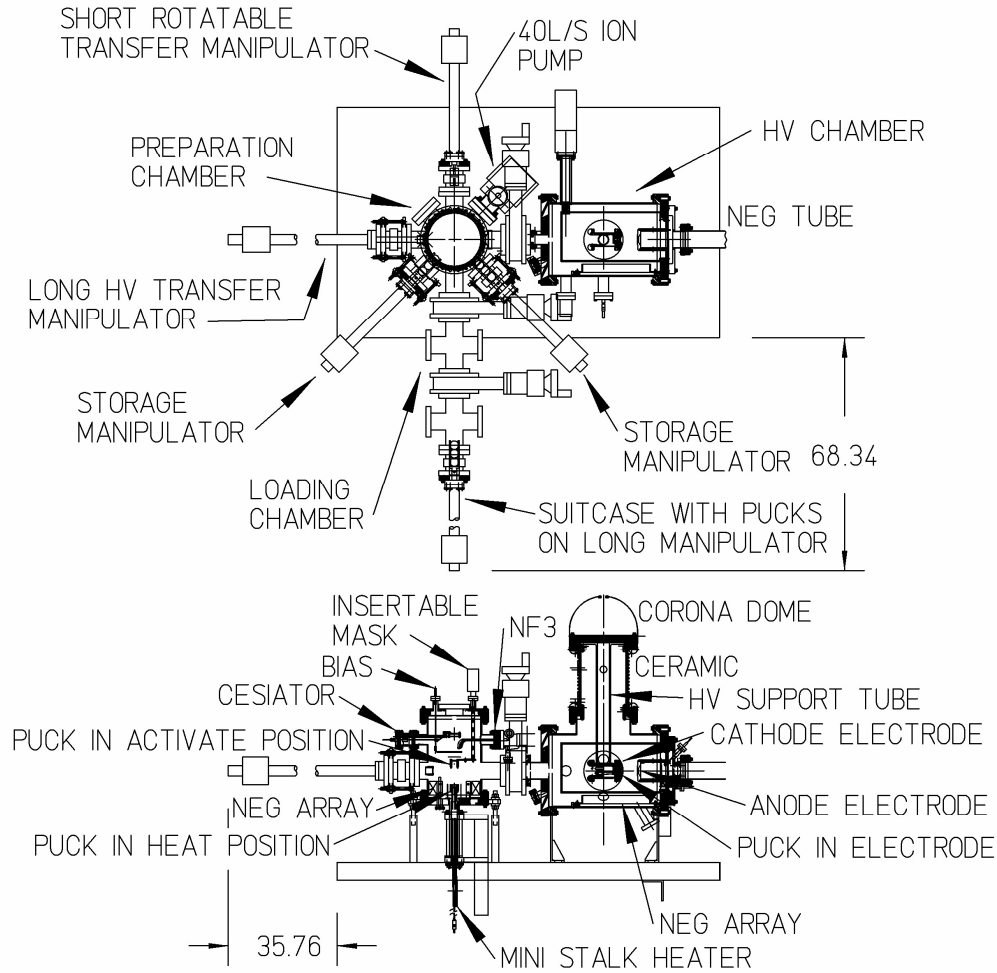


FIGURE 1. The new 100 kV DC high voltage load locked GaAs photogun; with (top) plan view of the four vacuum chambers and manipulators and (bottom) side view of the preparation and HV chambers.

Following activation, the valve between the preparation and HV chambers was briefly opened and the puck was quickly inserted into the cathode electrode. The HV chamber was fabricated using stainless steel (304), electro-polished and vacuum fired at 900°C and 3×10^{-6} Torr for 3 hours. The measured outgassing rate is $<10^{-12}$ Torr-L/s/cm². Outgassing from the chamber wall is suppressed by an applied NEG coating providing 200 L/s hydrogen pump speed. The chamber contains an array of commercial NEG modules (7200 L/s) and a 40 L/s DI pump. A commercial extractor gauge measures a base pressure of 8×10^{-12} Torr (corrected for hydrogen), a value inconsistent with expectation based on outgassing rate and pump speed measurements [11]. In all likelihood, actual pressure is significantly lower than indicated by the gauge. Gun vacuum increases to 1.1×10^{-11} Torr when open to the beam line vacuum. The “side ceramic” design minimizes the number of components at high voltage: the loading chamber, preparation chamber and most of the HV chamber are at ground potential. The modified Pierce-style cathode electrode has a 12.8 mm opening and 25

degree angled face. The anode electrode is aligned and supported from a flange on the front face of the HV chamber.

EXPERIMENT

The test apparatus for commissioning the new load locked gun was the same as that used previously [7-9] and is shown in Fig. 2. The electron beam exits the gun through a large bore (2.5 inch diameter) NEG-coated beam tube toward a 15 degree bend magnet. This bend allows illumination of the photocathode at normal incidence without using mirrors inside the vacuum chamber. Five solenoid magnets ($f \sim 50$ cm) and air core steering magnets were used to transport the beam 5.5 m to a Faraday cup that was previously degassed at 450°C for 24 hours to minimize outgassing and vacuum contamination at high current. In addition, two differential NEG pump stations provide beam line vacuum isolation from the Faraday Cup, a factor >100 . Gun and beam line vacuum are monitored by high resolution (<50 pA) ion pump power supplies. Viewers were used to verify proper beam transport through the center of all the solenoids and beam pipe. Magnetic shielding was added to uncovered beam pipe to dampen ambient DC and AC magnetic fields.

A Coherent Verdi-10 laser was chosen for these tests, to provide large QE expected at the operating wavelength 532 nm and to minimize the laser power required (<600 mW was used for all tests), thereby minimizing photocathode heating effects. The laser spot size was set by inserting a lens with appropriate focal length near the beam line vacuum window. The intensity profile of the laser beam was measured by diverting the beam, after the focusing lens, to a laser profile analyzer located at the photocathode distance. The laser intensity was remotely controlled using a polarization sensitive attenuator with high extinction ratio. This approach mitigated the need to use neutral density filters which enlarge and distort the laser profile. The laser power was occasionally measured using an in-line power meter inserted into the laser beam path, which interrupted beam delivery, or while running via a pick-off laser beam directed into a power meter calibrated to the in-line power meter.

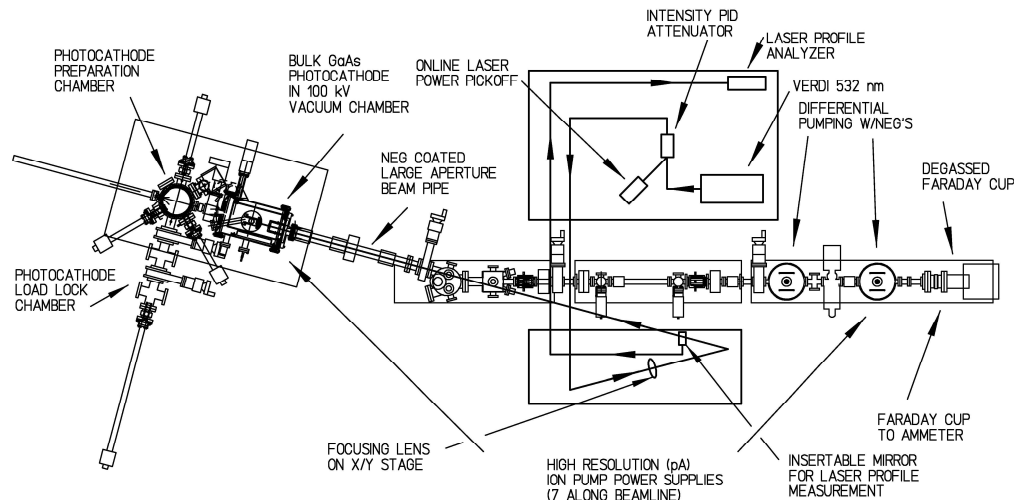


FIGURE 2. The new 100 kV DC electron photogun, beam line and laser system is shown.

Lifetime measurements were made at beam currents up to 10 mA and with two laser spot size diameters, 0.32 mm and 1.55 mm. A PID loop was used to automatically adjust the laser intensity attenuator to maintain constant current for each measurement. Before each measurement the vacuum condition and initial QE across the photocathode active area were measured. During the run, beam current at the Faraday cup, pick-off laser power and relative vacuum pressure at six ion pump locations evenly distributed along the beam line were recorded. Two similar photocathodes, each cut from the same wafer, were used for these measurements.

CHARGE LIFETIME RESULTS

Charge lifetime is defined as the amount of charge extracted from the photocathode before the quantum efficiency falls to $1/e$ of the initial value. Charge lifetime data obtained using the new load locked gun are shown in Fig. 3 (top), together with results from the original CEBAF load locked gun. Over a comparable range of beam currents > 1 mA, the new load locked gun exhibits improved charge lifetime performance by a factor between 2 and 3, for both laser spot sizes. Specifically, the new load locked gun provides charge lifetimes > 2000 C for the 1.55 mm laser spot size over a broad range of beam current from 1 to 7 mA and > 1000 C for the smaller 0.32 mm laser spot size for beam currents less than 1 mA. In addition, the charge lifetimes for the 0.32 mm laser spot size exceed 200 C over the entire range, representing a significant improvement over the original gun, particularly at 10 mA beam current. Some of the roughly two dozen charge lifetime results are inconsistent with the general trends. This is likely attributed to the difficulty maintaining constant operating conditions throughout the lengthy duration required to complete these measurements (months), including occasional loss of building power or access to the test facility, which involves cycling power to the laser, high voltage or hardware controls. In addition, as charge lifetime becomes very large, it becomes important to conduct very lengthy runs. Consequently, most runs were unattended and lasted many hours, often overnight, during which time, for example, small variations in test conditions might go unnoticed. Subtle, untracked, variations might have a large impact on a given charge lifetime result, for example, if laser pointing instability occurred and was not known.

As Fig. 3 indicates, the best charge lifetimes were achieved with the larger laser spot size. A simple geometric argument can be used to explain this behavior. Ions produced using a larger laser spot size will be distributed over a larger area of the photocathode and consequently, damage at any specific photocathode location will occur more slowly. Accordingly, for the laser spot size diameters studied for the new gun (0.32 mm and 1.55 mm) and the original gun (0.34 mm and 1.54 mm), charge lifetime should improve by a factor of about 22 when operating with the larger laser spot. Actual results however do not exhibit this enhancement: the original load locked gun provided a factor of 10 improvement when using the larger laser spot size and the new load locked gun a factor of 6. So although tests with both guns support the claim that a larger laser spot size provides improved charge lifetime performance, one cannot expect the simple model prediction.

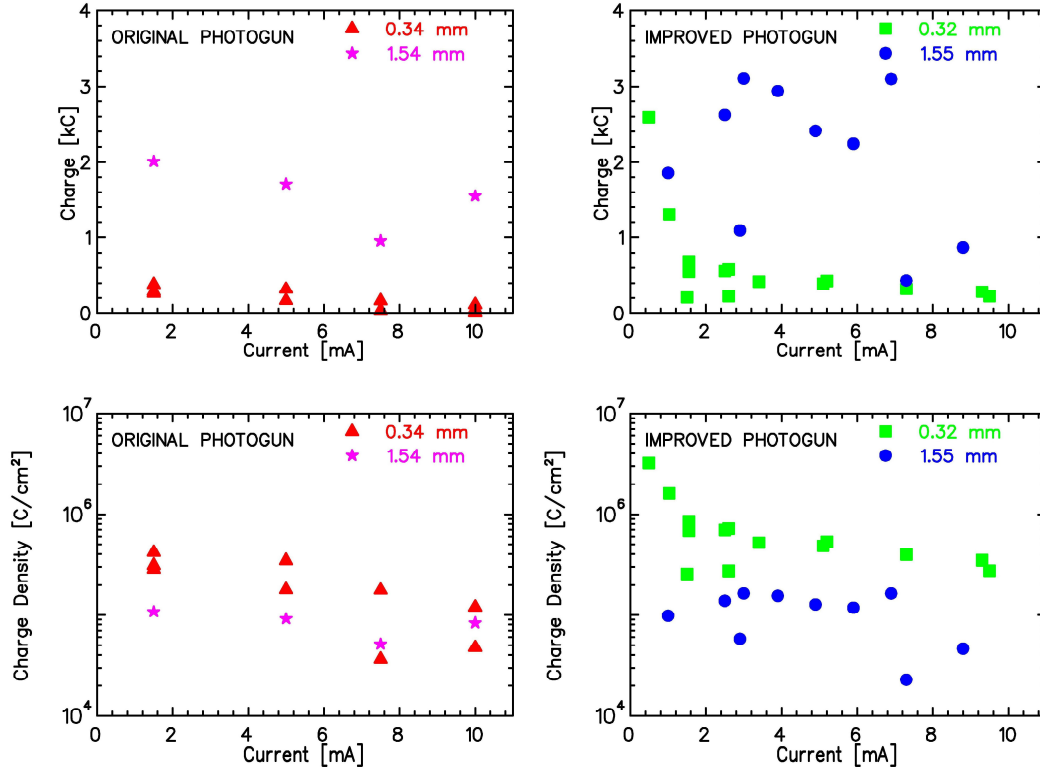


FIGURE 3. (Color) Charge lifetime (top) and charge density lifetime (bottom) for the original (left) and improved (right plots) load locked photoguns. Each plot shows two data sets corresponding to the two laser spot sizes used to test each photogun.

CHARGE DENSITY LIFETIME RESULTS

Besides predicting an enhancement in charge lifetime, the simple model also implies charge density lifetime should be a constant of the photogun. To explore the validity of this simple model premise, the charge lifetime data of Fig. 3 (top) were plotted in units of charge density in Fig. 3 (bottom). Not surprisingly, following the discussion of the charge lifetime results, this is not the case. Each laser spot size provides a different value of charge density lifetime and it is useful to consider possible explanations for this behavior.

The highest charge density lifetimes, for both guns, were obtained using the smallest laser spots sizes. This suggests that the cathode/anode geometry is not well suited to efficiently transport a large beam originating from the photocathode. Past experience with the CEBAF electrode structure indicated that the best photocathode lifetimes were obtained when only the center portion of the photocathode was activated [1]. Beam originating from the edge of the photocathode travels an extreme trajectory and sometimes electrons strike the vacuum chamber wall, degrading vacuum and hastening photocathode decay. For these tests, care was taken to ensure that only the central 5 mm diameter region of the photocathode was activated to NEA, however, the transmission of an electron beam emitted from even within this small

area might be sensitive to astigmatic aberration of the existing gun structure, particularly as the laser spot (and electron beam) size is increased.

One must also consider the complicated dynamics of ion production within the cathode/anode gap. Ions will be focused toward the electrostatic center of the photocathode and specific ion trajectories will depend on where the ion is created within the gap. Ion stopping depth within the photocathode will vary for different gas species and ionization cross section varies with electron beam energy, which ranges from 0 to 100 keV in the cathode/anode gap. As a result, one can expect to observe a different damage signature when running from different locations of the photocathode. In addition, ions that are created near the anode will strike closer to the electrostatic center of the photocathode. For these tests, the larger laser spot samples a wider range of radial locations. The portion closer to the electrostatic center will undoubtedly suffer more ion damage, while the portion at further radial locations less.

These factors (and likely others) can explain why simply increasing the laser spot size does not produce the anticipated enhancement predicted by the simple model. Nonetheless, plotting results as charge density lifetime is a very useful gauge of the photogun operation, and to the extent this quantity is further characterized should lead to design goals of a photogun that may take full, or maximum, advantage of the simple model premise.

CONCLUSIONS

The new CEBAF load locked gun exhibits impressive charge lifetime at milliAmpere beam currents, with demonstrated improvement over the original load locked gun design. The new load locked gun will soon be benchmarked against the vent/bake guns now delivering beam at CEBAF, using high polarization photocathode material and a drive laser with RF-pulsed light. We expect installation of this new load locked gun at CEBAF during a scheduled summer shutdown.

Research to better appreciate factors limiting photocathode lifetime will continue at the test facility using a similar load locked photogun. Future work will focus on measuring lifetime at high current and high polarization, with the goal of providing more than 1 mA of high polarization (~85%) electron beam for extended duration. In addition, studies to understand the sensitivity of the charge density lifetime on the cathode/anode structure will continue.

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REFERENCES

1. C. K. Sinclair *et al.*, submitted to *Phys. Rev. ST-AB*.

2. S. Benson *et al.*, *Nucl. Instrum. Meth. A* **429**, 27 (1999); other Jefferson Lab FEL-related publications are available at <http://www.jlab.org/FEL/felpubs/>
3. V. Ptitsyn *et al.*, “eRHIC, Future Electron-Ion Collider at BNL” in Proceedings of the 2004 European Particle Accelerator Conference, Lucerne, Switzerland.
4. Y. Derbenev *et al.*, “Electron-Ion Collider at CEBAF: New Insights and Conceptual Progress” in Proceedings of the 2004 European Particle Accelerator Conference, Lucerne, Switzerland.
5. L. Merminga *et al.*, “ELIC: An Electron-Light Ion Collider based at CEBAF” in Proceedings of the 2002 European Particle Accelerator Conference, Paris, France.
6. I. Bazarov *et al.*, “Phase 1 Energy Recovery Linac at Cornell University” in Proceedings of the 2002 European Particle Accelerator Conference, Paris, France.
7. J. Grames *et al.*, “Lifetime Measurements Using the Jefferson Lab Load-Lock Electron Gun” in Proceedings of the 2004 16th International Spin Physics Symposium, Mainz, Germany.
8. J. Grames *et al.*, “Ion Back-Bombardment of GaAs Photocathodes Inside DC High Voltage Electron Guns” in Proceedings of the 2005 Particle Accelerator Conference, Knoxville, Tennessee.
9. M. Poelker and J. Grames, “Operation of CEBAF Photoguns at Average Beam Current > 1 mA” in Proceedings of the 2005 XIth International Workshop on Polarized Sources and Targets, Tokyo, Japan.
10. The temperature is limited to about 150°C in order to preserve functionality of the magnetic manipulator vacuum couplings, which we have found degrade when heated repeatedly at 250°C.
11. M. Stutzman *et al.*, submitted to *Nucl. Instrum. Meth.*